

An Evaluation of the Applicability of Damage Tolerance to Dynamic Systems

Scott C. Forth

NASA Langley Research Center, MS188E, Hampton, VA, USA

Phone: (757) 864-3823; fax: (757) 864-8911; email: scott.c.forth@nasa.gov

Dy Le

FAA William J. Hughes Technical Center, Atlantic City Int'l Airport, NJ USA

Jay Turnberg

FAA Engine and Propeller Directorate, Burlington, MA USA

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Abstract

The Federal Aviation Administration, the National Aeronautics and Space Administration and the aircraft industry have teamed together to develop methods and guidance for the safe life-cycle management of dynamic systems. Based on the success of the United States Air Force damage tolerance initiative for airframe structure, a crack growth based damage tolerance approach is being examined for implementation into the design and management of dynamic systems. However, dynamic systems accumulate millions of vibratory cycles per flight hour, more than 12,000 times faster than an airframe system. If a detectable crack develops in a dynamic system, the time to failure is extremely short, less than 100 flight hours in most cases, leaving little room for error in the material characterization, life cycle analysis, nondestructive inspection and maintenance processes. In this paper, the authors review the damage tolerant design process focusing on uncertainties that affect dynamic systems and evaluate the applicability of damage tolerance on dynamic systems.

Introduction

The United States Air Force damage tolerance initiative [1] revolutionized the life cycle management of aircraft fuselage and wing systems. Routine inspection of structure for cracks and retirement for cause replaced fixed-operating time, safe-life retirement requirements, saving the Air Force millions of dollars in un-needed replacement costs. The standard damage tolerance life management methodology naturally reflects the airframe operating environment where it was first implemented: low numbers of cycles per flight hour, physically large, readily detectable damage, benign thermal cycling, relatively simple inspection processes, etc. Therefore, the life cycle analyses and material characterization methods focus more on crack propagation than nucleation because cracks can stably propagate under airframe loading conditions for extended periods of time without compromising structural integrity; the inspection methods focus on rapidly detecting substantial cracks in physically large, unobstructed areas as defined by the airframe and wing structure; and the repair procedures and life extension methods

focus on cost-effective patches and repairs that are localized with the presumption that the remaining structure will be reliable.

Unfortunately, the assumptions and practices used for airframes have little bearing in dynamic systems. Recently, the FAA, NASA and the propeller and rotorcraft industries have teamed together to develop methods and guidance for the safe management of dynamic systems using a damage tolerance approach similar to that developed by the Air Force. Aircraft propeller and rotorcraft dynamic systems experience millions of vibratory cycles per flight hour [2, 3], orders of magnitude greater than an airframe loading spectrum. If a crack develops in these systems, the time to failure is extremely short, less than 100 flight hours in most cases [4, 5, 6], leaving little room for error in the material characterization, life cycle analysis, inspection, and maintenance processes. Therefore, a thorough understanding of the crack nucleation mechanisms in these dynamic systems will lead to more focused material characterization, life cycle analysis and inspection programs, and ultimately safer aircraft. In this paper, the authors will first describe dynamic systems, then discuss the damage tolerance method for life cycle management, evaluate uncertainties in dynamic systems that affect damage tolerance and comment on the applicability of damage tolerance to dynamic systems.

Dynamic Systems

The dynamic systems in aircraft, such as engines, propellers, transmissions, etc., are loaded via high frequency vibrations, contrary to the near-steady pressure or aerodynamic load of an aircraft fuselage or wing. For instance, during spin-up, a helicopter main rotor system may experience cross-winds that excite the natural frequency of the propeller resulting in additional vibrational loads within the rotor system, above and beyond the mechanical vibrations caused by the engine, the aerodynamic interference with the fuselage, the aerodynamic forces applied from generating thrust, etc. For comparison purposes, a rotorcraft fixed pitch link, which is a dynamic component, is shown in Figure 1 along with the loading spectrum FELIX [7, 8] for the initial portion of one flight (the entire spectrum is not shown because one flight hour consists of over 1.2 million cycles). An aircraft wing structure is shown in Figure 2 along with the loading spectrum TWIST [9] for three flights (the typical (top left) flight hour consists of 100 cycles). A comparison of the loading spectra presented in Figures 1 and 2 reveals that the FELIX spectrum contains 12,000 times more cycles per flight hour than the TWIST spectrum. This increase in cycles from the usage environment is the challenge that faces implementing a damage tolerance approach to life management in dynamic systems.

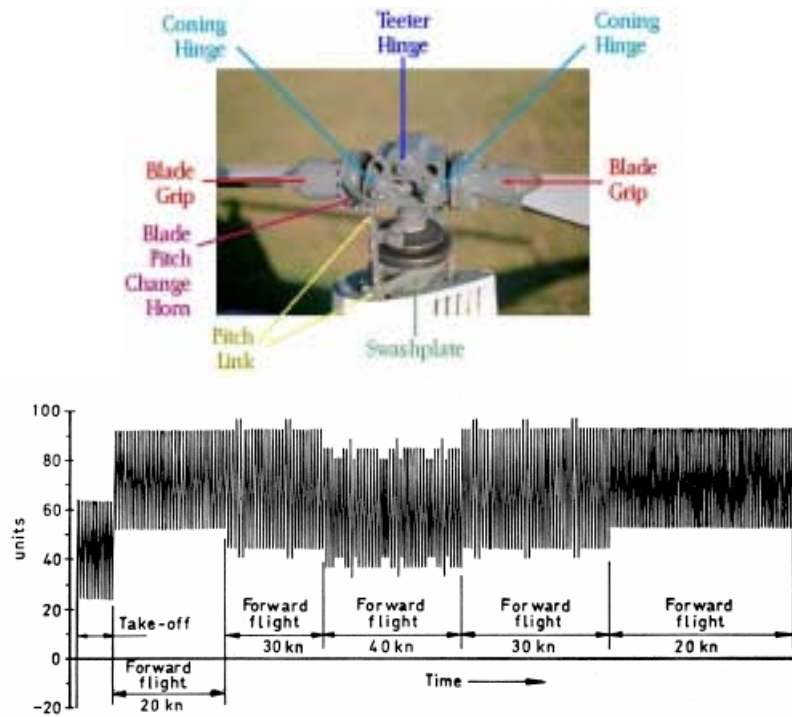


Figure 1: Photograph of a rotorcraft pitch link assembly and the corresponding stress spectrum FELIX.

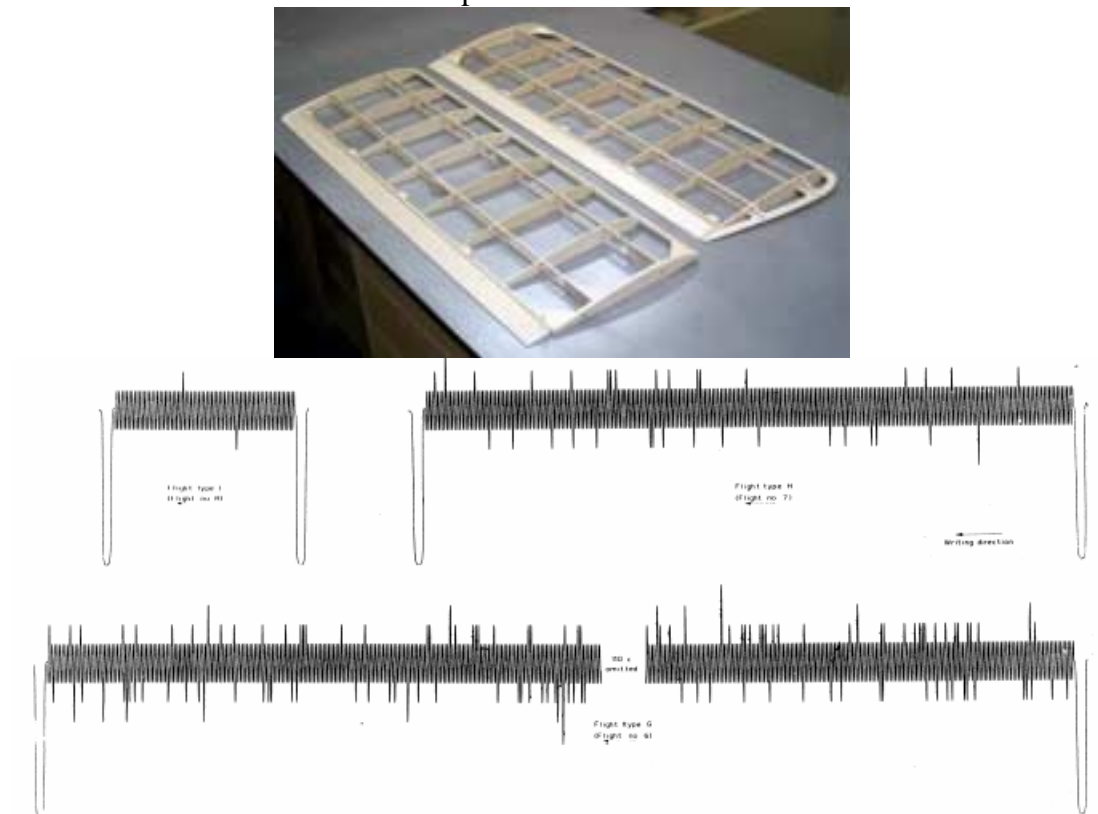


Figure 2: Photograph of typical wing construction and the corresponding stress spectrum TWIST.

Damage tolerance

The damage tolerance philosophy to design and maintain an aircraft structure revolves around safe operation with the existence of damage. The United States Air Force has set the standard for the “damage” in damage tolerance to be synonymous with cracks, since most structures ultimately fail from crack propagation [1]. Therefore, the *damage tolerance philosophy is reliant on the ability of the manufacturer to predict the fundamental physics of crack growth and reliably find the cracks in service*. The damage tolerance design approach can be broken down into easily definable, technically independent sections. The first such section is usage, which defines the operational environment of the system such as loading levels, likelihood of corrosion, probability of impact damage occurring, etc. The second section is nondestructive inspection, which defines life-cycle management through inspection interval designation and also defines the initial and final crack sizes to be used in the damage tolerant design. The third section is fatigue crack growth, which defines material properties, crack growth modeling and life prediction. The fourth section is residual strength, which builds on the fatigue crack growth analyses to predict the onset of structural failure. The fifth and final section is repairability, which defines life cycle cost. Each of these sections will be discussed in the order presented to outline the requirements for a damage tolerant design.

To illustrate the impact uncertainty in each of the sections has on the overall damage tolerance of the component, a simple variability study on the damage tolerance of the pitch link (Figure 1) described previously is assessed using the NASGRO 4.11 computer code [10] to predict the fatigue crack growth time to failure. The assumptions made to perform the damage tolerance assessment are:

- 1) The FELIX loading spectrum will be used with a +/- 10% variability on the mean load as defined by a rotorcraft manufacturer.
- 2) The inspection methods will be penetrant and eddy current with a +/- 10% variability on detectable crack size reported in Table A-1.
- 3) The component will be made of 7075-T73 aluminum and the fatigue crack growth rate and fracture toughness properties from the NASGRO material database will be varied by +/- 10% on stress intensity.
- 4) For this study, repairability will not be directly addressed and the part geometry will be considered fixed as a single crack emanating from a hole in a plate.

The results of this study and any relevant data from the literature will be discussed in each section.

Usage

The usage of a dynamic system defines several aspects of operation, such as loading configurations, environmental effects on the material or joints, and the exposure of the system to debris, foreign object damage, etc. One aspect of the system usage environment is defined by a loading spectrum such as FELIX, presented schematically in Figure 1, used in the damage tolerance analyses for life prediction. Environmental effects, such as corrosion or material degradation, and foreign object damage, such as metal shavings in the gear oil causing fretting, will be taken into account for material selection and setting nondestructive inspection intervals. In this paper, the authors will focus on the loading spectrum because it is easier to quantify variability in loads than

environmental effects. The loading spectrum used in a damage tolerance assessment is typically defined by:

1. response of similarly designed parts on aircraft already flying;
2. strain-gage measurements taken during component level testing in the laboratory;
3. strain-gage measurements taken during flight test;
4. operator feedback to define the number of maneuvers performed during flight;

The usage environment is the most critical aspect of a damage tolerance assessment, as it is the first piece of information used to design the system and is used to define inspection intervals and allowable materials.

Results from the uncertainty study of the pitch link, defined previously, are presented in Figure 3 showing that a 20% (+/- 10%) change in mean stress of the FELIX spectrum (Figure 1) resulted in a 76% change in fatigue life. Research found in the literature also concludes that small variations in the usage loading spectrum had sizeable effects on the predicted fatigue life of a dynamic system [2, 3, 5, 6]. Therefore, the loading spectrum of each component must be defined very accurately to predict the damage tolerance of the dynamic system.

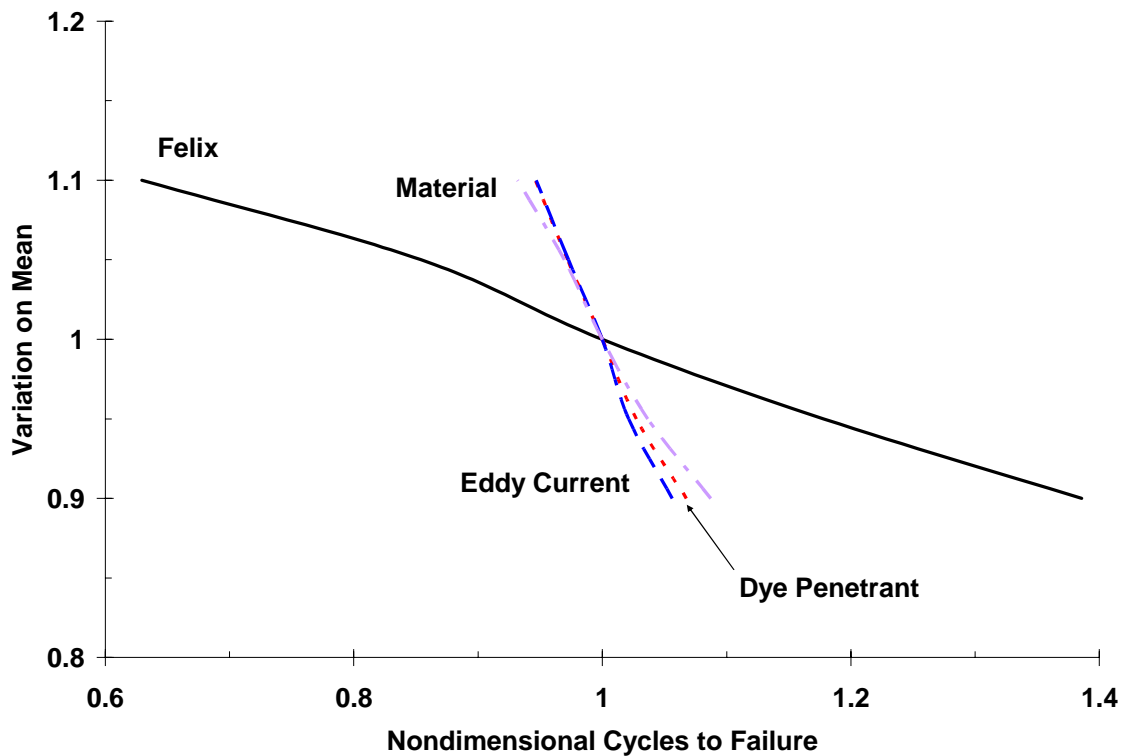


Figure 3: Affect of uncertainty in loading spectrum, inspection methods and material properties on predicted fatigue life.

Nondestructive inspection

Nondestructive inspection methods are simply defined as inspection techniques that look for cracks and do not damage the structure being inspected. These methods can range from fluorescent dye penetrant that is sprayed on the surface to find cracks to complex eddy-current arrays that scan through multiple material layers searching for embedded

cracks. Based on which method is chosen as both the safest and most economical, a detectable crack size to be used in the damage tolerance analyses can be determined. The detectable crack size is established from:

1. material response (for instance some materials can be inspected using eddy current whereas some are not conductive enough);
2. structural configuration (for example a flat sheet of material is easier to inspect than a layered, curved material that is difficult to access);
3. probability of detection (how reliable the method can detect a crack of a given size for the structural geometry);
4. inspection method (for instance ultrasonic inspection has a much finer resolution than fluorescent dye penetrant);
5. cost (it may cost an operator 5 – 10 times the manpower and downtime to perform an ultrasonic inspection than a fluorescent dye penetrant).

Based on the material and structural configuration an inspection method may be chosen first based on cost of implementation. The designer will then have a probability of detection matrix to work with for the specific inspection method that will give an initial crack size to be used in the fatigue crack growth and residual strength analyses. An example of an initial crack size matrix based on a 90% probability of detection with 95% confidence is shown in Table 1 for the International Space Station [11]. The results of fatigue crack growth and residual strength analyses will dictate whether the current inspection process is adequate, or if a different technique may yield a better life cycle estimate. Typically, the selection and subsequent implementation of an inspection method is an iterative process.

Uncertainties in the inspection process leads to variability in the initial crack size used for the damage tolerance analyses. The results from the pitch link analysis presented in Figure 3 show that a variation of 20% in the detectable crack size from penetrant resulted in a 12% change in fatigue life. Additionally, a variation of 20% in the detectable crack size from eddy current resulted in an 11% change in fatigue life. The results of the pitch link study imply that the damage tolerance analyses are insensitive to initial crack size. However, it is important to note that the stress levels, component geometry and inspection methods chosen for the pitch link study influence the results. For instance, the mean time to failure for the pitch link analyses was approximately 13 hours. Typically, a dynamic component will be designed to a minimum acceptable fatigue crack growth life of 1,000 hours. In the pitch link study, the time to failure was short because the detectable crack size was too large at the given stress levels to provide an acceptable crack growth life. A similar study performed by Everett [6] using the FELIX spectrum showed that initial crack length of 0.036 mm, an order of magnitude smaller than any crack size shown in Table 1, was required to achieve an acceptable crack growth life. Therefore, the pitch link study, in combination with the literature, has shown that the damage tolerance of a dynamic system is insensitive to detection methods because current NDI methods cannot reliably detect a crack small enough to provide reasonable life of dynamic components.

TABLE 1: Minimum Initial Crack Sizes for Fracture Analysis
Based on Standard NDE Methods

SI UNITS (mm)¹

Crack Location	Part Thickness, t	Crack Type	Crack Dimension, a	Crack Dimension, c
<u>Eddy Current NDE</u>				
Open Surface	t ≤ 1.270	Through PTC ²	t	1.270
	t > 1.270		0.508	2.540
			1.270	1.270
Edge or Hole	t ≤ 1.905	Through Corner	t	2.540
	t > 1.905		1.905	1.905
<u>Penetrant NDE</u>				
Open Surface	t ≤ 1.270	Through PTC	t	2.540
	1.270 < t < 1.905		t	3.810 - t
	t > 1.905		0.635	3.175
			1.905	1.905
Edge or Hole	t ≤ 2.540	Through Corner	t	2.540
	t > 2.540		2.540	2.540
<u>Magnetic Particle NDE</u>				
Open Surface	t ≤ 1.905	Through PTC	t	3.175
	t > 1.905		0.965	4.775
			1.905	3.175
Edge or Hole	t ≤ 1.905	Through Corner	t	6.350
	t > 1.905		1.905	6.350
<u>Radiographic NDE</u>				
Open Surface	0.025 ≤ t ≤ 0.107	PTC	0.7t	1.905
	t > 0.107		0.7t	0.7t
<u>Ultrasonic NDE</u> Comparable to a Class A Quality Level (MIL-STD-2154)				
Open Surface	t ≥ 2.540	PTC	0.762	3.810
			1.651	1.651

¹ 1 mm = 0.039 inches

² PTC - Partly through crack (Surface Crack)

Fatigue Crack Growth

The fatigue crack growth analyses predicts the time to structural failure based on usage from a given initial crack defined by the nondestructive inspection process. The analyses incorporate fracture mechanics algorithms and material response data to relate the crack growth rate to the structural configuration, local stress state, loading spectrum and crack configuration. The fracture mechanics algorithms have been developed by agencies such as the USAF and NASA for the damage tolerance certification of their respective flight hardware. These computational tools have incorporated common material properties,

structural configurations and crack shapes into large databases with simple user interfaces that design engineers can use for damage tolerance assessments. The material response data is generated using ASTM standards and large commercial material databases have formed to support the use of common material forms. The prediction of the fatigue crack growth life is dependent upon:

1. material response (for instance cracks of a similar size may grow at very different rates in the same material based on microstructural orientation);
2. structural configuration (for example a crack growing from a hole typically propagates faster than a crack in a flat panel);
3. local stress state (if the structure is shot-peened the residual stresses must be accounted for to obtain an accurate life prediction);
4. loading spectrum (the rate of occurrence and sequence of loads can have drastic effects on the crack growth rate);
5. crack configuration (for instance a corner crack will propagate at a different rate than a through-thickness crack).

The results of the fatigue crack growth analyses will define the operable life and inspection interval of the structure with an inherent source of damage, the initial crack. If the total fatigue crack growth life and inspection interval (a fraction of the total life) are adequate, a residual strength analysis may be conducted. If the fatigue crack growth life or inspection interval are unacceptable, either a new inspection method may be chosen to generate a smaller initial crack size; a different material system may be chosen to improve fatigue response; the structural configuration may be changed to reduce stress concentrations; shot-peening or cold working may be applied to modify the residual stress state in the component; and/or the operational loading spectrum may be modified to reduce the number of cycles or severity of stress the structure experiences in service, all with the intent of improving the total fatigue life or time between nondestructive inspections. This process is also typically iterative, resulting in design detail changes or variations in the nondestructive inspection frequency or method.

The uncertainties associated with the material properties ($\pm 10\%$ on the stress intensities in the da/dN vs. ΔK data) resulted in a 16% change in the crack growth analyses performed in the pitch link study as shown in Figure 3. Once more, the initial crack size defined by the nondestructive inspection method resulted in crack growth rates in the linear portion of the crack growth rate curve that are relatively insensitive to minor changes such as those used in the pitch link study. Additionally, results reported in the literature state that if the initial crack size is small, then variations in the material properties play a role, *i.e.* if the initial stress intensities are near the fatigue crack growth threshold [3, 6]. Therefore, if the inspection method can reliably detect small enough cracks to provide a reasonable life estimate, then uncertainties in the material properties can be influential in predicting damage tolerance. Otherwise, the damage tolerance analyses are insensitive to uncertainties in the material properties.

Residual Strength

The residual strength of a structure is defined as the maximum load carrying capability with the existence of damage, in this case a crack. The residual strength of the structure is critical in defining safe operating margins. The structure must be able to withstand a design limit load (a percentage of the material ultimate strength) with the initial crack

defined by the nondestructive inspection method. Furthermore, the structure must be able to carry some percentage of the limit load throughout the fatigue crack growth life. Consequently, the residual strength and fatigue crack growth analyses must be completed in tandem, even though the two are technically independent. The residual strength analyses are dependent upon:

1. material response (for instance toughness varies significantly between materials);
2. structural configuration (for example a crack may arrest at a tear strap, significantly improving residual strength);
3. loading spectrum (the design limit load may be significantly higher than any of the predicted service load levels resulting in higher safety margins);
4. crack configuration (for instance a surface crack has significantly higher fracture toughness than a through-thickness crack in the same material).

The results of the residual strength analyses will define the safety margins the structure will maintain while sustaining damage. If the residual strength is adequate for an acceptable range of crack sizes defined in the fatigue crack growth analyses and inspection process then a safety margin is readily definable. The safety margin will be used to evaluate the structural integrity from unforeseen changes in usage, discrete source damage and/or neglected nondestructive inspections. The residual strength analyses are often used like a static design allowable with a specific final crack length in mind prior to the selection of a nondestructive inspection method, because the maximum residual strength crack length is traditionally much larger in thin-gage fuselage structure than the minimum detectable inspection crack size. In that same notion, the residual strength analyses have typically been performed before the fatigue crack growth analyses because it is less time consuming and requires significantly less data.

The uncertainties in the material properties ($\pm 10\%$ of K_{IC}) used for the residual strength analysis of the pitch link resulted in negligible changes in the predicted failure load ($\pm 3\%$) or final crack length ($\pm 3\%$). The results of the pitch link analyses combined with results presented in the literature [5] confirm that variability in the materials properties used to compute residual strength has very little bearing on the damage tolerance of a dynamic system because the useful design life is used prior to a crack propagating near the residual strength limit.

Repairability

Repairability is critical to the cost of operating and maintaining aerospace structures. If a structure is readily, and economically, repairable it will be much easier to manage in service than something that requires significant downtime and specialized training to repair, or replace. To design for both damage tolerance and repair is not a trivial task. Complex, built-up structures are excellent in damage tolerance yet are difficult to repair in the field. However, new repair technologies, such as bonded patches, and localized welded repairs that can be performed in the field, can be considered during the design process to improve repairability of high-fidelity, complex structure. Repairability does not directly affect the damage tolerance design process like the other technologies previously discussed. However, the designer must maintain a firm understanding that whatever structural configuration is designed will be damaged in service and must be economically repairable. Uncertainties in repairability are difficult to quantify for a variability study and are therefore not investigated thoroughly. Based on results

presented in the literature [2], dynamic components are typically replaced instead of repaired for cost.

Discussion

Uncertainty in the nondestructive inspection process is the most critical component of robust damage tolerant management of aircraft fuselage and wing structure [12]. Negligence of inspection procedures causes far more field incidents than any of the other components of a damage tolerance process [13], such as marginal definition of the fatigue crack growth response of the material. Aircraft historically experienced localized component failure regularly because the material properties and usage spectrum were ill-defined [14]. Focused research into structural failure mechanisms and usage monitoring lead to well defined testing and computational procedures resulting in improved design allowables leading to safer systems [15]. However, as research and development has improved the resolution of inspection methods, aircraft manufacturers have raised design allowables to lighten the structure while maintaining the current margin of safety. Therefore, nondestructive inspection will remain the largest source of variability and risk in the safety of airframe and fuselage systems [16].

In contrast to the airframe environment, little research and development has been performed on dynamic system damage tolerance because manufacturers design and manage dynamic systems using safe-life replacement methods [2, 3]. To date, studies performed in the 1990's by Cronkite, et al [2], Nicholas [3], Lincoln and Yeh [5] and Everett [6] have been the benchmark for damage tolerance analyses of dynamic systems. Each author concluded that small variations in usage had the greatest effect on the damage tolerance of a dynamic system. Similarly, the pitch link study presented in this paper showed that variability in the loading spectrum had the largest affect on the predicted fatigue life, where a 20% (+/- 10%) change in mean stress resulted in a 76% change in fatigue life (Figure 3). Whereas, a variation of 20% in the material properties resulted in a 16% change in fatigue life; a variation of 20% in the detectable crack size from penetrant resulted in a 12% change in fatigue life; and a variation of 20% in the detectable crack size from eddy current resulted in an 11% change in fatigue life. The loading spectrum had the greatest influence because cracks of an inspectable size propagate so rapidly in a dynamic system that variations in inspectable crack size, crack growth rate and residual strength are negligible.

The predicted time to failure for the pitch link was 13 hours. Based on discussions with rotorcraft operators, the current acceptable replacement time for a pitch link is 1,000 hours. Therefore, the damage tolerance analysis is predicting component failure prematurely. The primary reason for the discrepancy between the life prediction of 13 hours and the component replacement time of 1,000 hours is because the initial crack size used in the analyses is too large. The options for increasing the predicted damage tolerance life are to lower the stresses or detect a smaller crack. To achieve a 1,000 hour lifetime, the mean stresses in FELIX would need to be lowered by nearly 80% or the detectable crack size would need to be lowered by two orders of magnitude. Lowering the stresses by 80% to justify a damage tolerance analysis is absurd because pitch links in service last 1,000 hours at the full level of the loading spectrum. Reliably detecting cracks of 0.036 mm, to use Everett's numbers [6], is impractical at a depot level as the inspectable crack sizes presented in Table 1 are considered the best possible by each

inspection method. Based on the results of the pitch link analyses and the results presented in the literature, the damage tolerance life management of a dynamic system is currently unrealistic.

Summary

Aircraft propeller and rotorcraft dynamic systems can accumulate millions of vibratory cycles per flight hour, more than 12,000 times the rate of aircraft fuselage and wing structure. If a crack develops in these systems, the time to failure is extremely short, less than 100 flight hours in most cases, leaving little room for error in the material characterization, life cycle analysis, nondestructive inspection and maintenance processes. A case study was performed of a helicopter rotor pitch link showed that small perturbations in the accuracy of the loading spectrum led to more than a factor of two change in the predicted fatigue life, whereas variations in material properties and inspection accuracy had minor affect. The conclusions of the case study support those found in the literature, specifically that:

1. the crack growth based damage tolerance method is too sensitive to small changes in loading spectrum
2. current nondestructive inspection methods cannot find cracks small enough to provide the life necessary to manage a dynamic system via damage tolerance.

Therefore, at this time with the inspection technologies available, crack growth based damage tolerance is not viable means to predict and manage the life cycle of a dynamic system.

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